PATENT APPLICATION

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the Application of

Takao ABE et al. | Group Art Unit: 1765

Application No.: 09/743,982 | Examiner: M.A. Anderson

Filed: January 18, 2001 | Docket No.: 108360

For: SILICON SINGLE CRYSTAL AND WAFER DOPED WITH GALLIUM AND METHOD FOR PRODUCING THEM

DECLARATION UNDER 37 C.F.R. §1.132

Director of the U.S. Patent and Trademark Office
Washington, D.C. 20231

Sir:

I, Takao Abe, a citizen of Japan, hereby declare and state:

1. I have a doctoral degree in Engineering, conferred upon me by the Faculty of Engineering of Hokkaido University in Japan in 1985.

2. I have been employed by Shin-Etsu Handotai Co., Ltd. since 1964 and I have had a total of 40 years of work and research experience in dislocated and dislocation-free silicon single crystals. The growing mechanism of intrinsic point defects and the suppression of point defects by doping nitrogen are particular subjects of my research. For these results, the Japan Association of Crystal Growth gave me the Paper Award in 1991. The demonstration of gallium-doped CZ crystals for solar cell application is one of these results. I have also performed research in the field of silicon-on-insulator structures created by wafer bonding techniques. These silicon-on-insulator structures are used for

advanced ULSI devices. In addition, for mass production, I have contributed to developments regarding the growth of dislocation-free FZ and CZ crystals, as opposed to dislocated crystals, and larger diameter FZ and CZ crystals from 10 mm FZ to 300 mm CZ crystals. Regarding other wafering processes, I developed, 15 years ago, new surface grinders to create flatter surfaces for bonded silicon-on-insulator wafers. These surface grinders are now popular in wafer technology. I was also involved in the development of many evaluation and characterization processes and equipment. The Solid State Devices and Materials (SSDM) Award was given by the Japanese Society of Applied Physics for the evaluation work by the technique of photoluminescence in cooperation with the public institution in 1992.

3. I am a member of the Electrochemical Society, the Japanese Society of Applied Physics and the Japanese Society of Physics. I was a co-organizer and co-chairman of the Silicon Materials Symposium and the Semiconductor Wafer Bonding Symposium from 1977 until 2001 in the Electrochemical Society Meetings held in the United States.

4. I have applied for over 80 patents in Japan, and over 40 in the United States, of which 10 have been issued, and I have filed more than 200 other foreign applications.

5. I have published numerous papers in this field, and applied for patents in the United States, Japan and other countries. In total, I have published more than 30 research papers in Japanese and more than 60 in English.

6. Among the papers on which I am listed as an author are S. W. Glunz et al., 100 cm^2 Solar Cells on Czochralski Silicon with an Efficiency of 20·2%, *Prog. Photovolt. Res. Appl.* 2000, Vol. 8, pp. 237-240 and S.W. Glunz et al., Comparison of Boron- and Gallium-doped p-Type Czochralski Silicon for Photovoltaic Application, *Prog. Photovolt. Res. Appl.* 1999, Vol. 7, pp. 463-469. These papers, written by researchers at the Fraunhofer Institute for Solar Energy Systems (Fraunhofer Institut Solare Energiesysteme) (Fraunhofer ISE) in Freiberg, Germany, report the results of their independent comprehensive testing of solar-cell-grade silicon single crystals, supplied by Shin-Etsu Handotai, and their conclusions from those tests. My contribution to these papers was the provision of solar-cell-grade silicon single crystals for testing, comparison and independent verification of the properties and unexpected results of the invention.

7. The silicon single crystals tested by the researchers at the Fraunhofer ISE were produced by the Czochralski method using a quartz crucible, having a large area, and including gallium as the dopant to control resistivity.

8. S.W. Glunz et al., Comparison of Boron- and Gallium-doped p-Type Czochralski Silicon for Photovoltaic Application, *Prog. Photovolt. Res. Appl.* 1999, Vol. 7, pp. 463-469, reports the results of comparative testing by the Fraunhofer ISE of gallium-doped quartz-crucible Czochralski silicon single crystals, boron-doped quartz-crucible Czochralski silicon single crystals and boron-doped Magnetic Czochralski crystals and Floating Zone crystals having little or no oxygen content. These results are summarized in Table 1 on page

465. Although all of the materials tested had similar conversion efficiencies prior to illumination, the gallium-doped quartz-crucible Czochralski silicon single crystals were found to have little or no light degradation or loss of conversion efficiency, with results comparable to those of boron-doped quartz-crucible Czochralski silicon single crystals. Figures 1 and 3 illustrate that, while boron-doped quartz-crucible Czochralski silicon single crystals experienced significant losses of lifetime and conversion efficiency after light illumination, the gallium-doped quartz-crucible Czochralski silicon single crystals maintained both lifetime and efficiency. In fact, a record efficiency of 22.5% for a gallium-doped quartz-crucible Czochralski silicon single crystal was confirmed. See *Prog. Photovolt. Res. Appl.* 1999, Vol. 7, p. 467.

9. S. W. Glunz et al., 100 cm^2 Solar Cells on Czochralski Silicon with an Efficiency of 20·2%, *Prog. Photovolt. Res. Appl.* 2000, Vol. 8, pp. 237-240, reports that the Fraunhofer ISE found that the gallium-doped, oxygen-contaminated Czochralski silicon single crystal solar cells can be produced having high conversion efficiencies, up to 20.2%, and without the lifetime degradation found in similarly grown, standard boron-doped Czochralski silicon. See *Prog. Photovolt. Res. Appl.* 2000, Vol. 8, p. 237.

10. I and/or those under my direct supervision and control have compared the areas and conversion efficiencies of boron- and gallium-doped silicon single crystal solar cells currently known. A graph summarizing this comparison, including the source and approximate date of the solar cell's development, is attached hereto and discussed in the following paragraphs.

11. The attached graph represents the development over time of silicon single crystal solar cell technology by plotting the cell area in square centimeters on the abscissa and the percent conversion efficiency on the ordinate for a number of representative solar cells. We have represented boron-doped silicon single crystal solar cells by blue dots and gallium-doped silicon single crystal solar cells by red dots.

12. As indicated by the double ended arrows along the ordinate axis, laboratory research studies are generally limited to silicon single crystal solar cells of less than 25 cm^2, and the size range for silicon single crystal solar cells being produced today is between 100 cm^2 and 150 cm^2. In the future, it would be desirable to develop large-area solar cells, such as those with areas in the range of 225 cm^2 and 314 cm^2 (as indicated by the arrow along the right side of the ordinate), that are not subject to loss of conversion efficiency due to photo-degradation. The dashed box in the upper right hand corner of the graph shows where the potential for further developments existed, and the red dots therein represent sizes and conversion efficiencies that the combination claimed in the above-captioned patent application can achieve.

13. Gallium-doped silicon single crystal solar cells having conversion efficiencies of 20-21% and maximum cell areas of 100 cm^2 had been achieved by way of the presently claimed invention by the end of 1999.

14. At present, a number of corporations and researchers have developed solar cells having larger areas, between 100 cm^2 and 150 cm^2, but these cells, made from boron-doped silicon single crystals, have conversion efficiencies in the range of about 13% to about 17%. Of these, Sharp has

prepared one of the largest solar cells, a silicon single crystal solar cell having an area of 150 cm^2 and a conversion efficiency of around 17%. Panasonic has demonstrated the ability to prepare solar cells having conversion efficiencies of around 16%, in sizes ranging between 100 cm^2 and 150 cm^2. BP, like Panasonic, has prepared a silicon single crystal solar cell having an area of 150 cm^2 and a conversion efficiency of between 15 and 16%. Shell, like Panasonic, has demonstrated the ability to prepare solar cells in sizes ranging between 100 cm^2 and 150 cm^2, but having conversion efficiencies only in the range of about 13.5 to 15%. In addition, because of photo-degradation due to boron-oxygen pairings, these solar cells are susceptible to decreasing conversion efficiencies.

15. None of these boron-doped silicon single crystal solar cells approaches the conversion efficiency achieved by the claimed combination of producing the crystal according to the Czochralski method using a quartz crucible, adding gallium as a dopant that controls resistivity of the crystal, using the gallium in an amount that produces a resistivity of 0.1 to 5 $\Omega \cdot cm$ (claims 20, 22, 24, 27-42, 46 and 48), or a gallium concentration of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3 (claims 21, 44, 47 and 49), forming the single crystal with a diameter of four inches or more, and using the single crystal for a solar cell.

16. Further evidence of the fact that the highest conversion efficiency that had been obtained in a large-size Czochralski silicon single crystal solar cell was about 17.5%, appears in the attached document, <u>Fraunhofer ISE PV Charts: Assessment of PV Device Performance,</u> 11th ed. (1998), silicon cells monocrystalline. The Fraunhofer ISE PV Charts list certified solar cell data measured at the Fraunhofer ISE. For each silicon single crystal solar cell tested

by Fraunhofer ISE, the chart lists the measured conversion efficiency at standard conditions with the accompanying measurement uncertainty, whether the solar cell is a laboratory or production cell, the cell area, the manufacturer and remarks, along with some additional properties and data, such as the testing date. As discussed in the explanatory section on "How to Read the ISE PV Charts," cell area and efficiency are both important factors in evaluating a solar cell, since "[l]arge area solar cells tend to show lower efficiencies than small area cells of corresponding technology."

17. A 100.50 cm^2 Czochralski silicon single crystal solar cell having a conversion efficiency of only about 17.5% is reported as the twenty-seventh entry of the "silicon cells monocrystalline" section of the Fraunhofer ISE PV Charts. I believe this was a boron-doped solar cell. All of the other about 100 cm^2 or larger cells had even lower conversion efficiencies.

18. As noted in the attached chart, the claimed invention has the potential to achieve a previously unaccomplished feat: producing a solar cell from a silicon single crystal having a high oxygen concentration due to quartz crucible dissolution during manufacture by the Czochralski method, a large area (such as achieved with the claimed diameter of at least four inches), using gallium as the dopant to control resistivity, and capable of having a conversion efficiency of over 20% that can be maintained without significant photo-degradation.

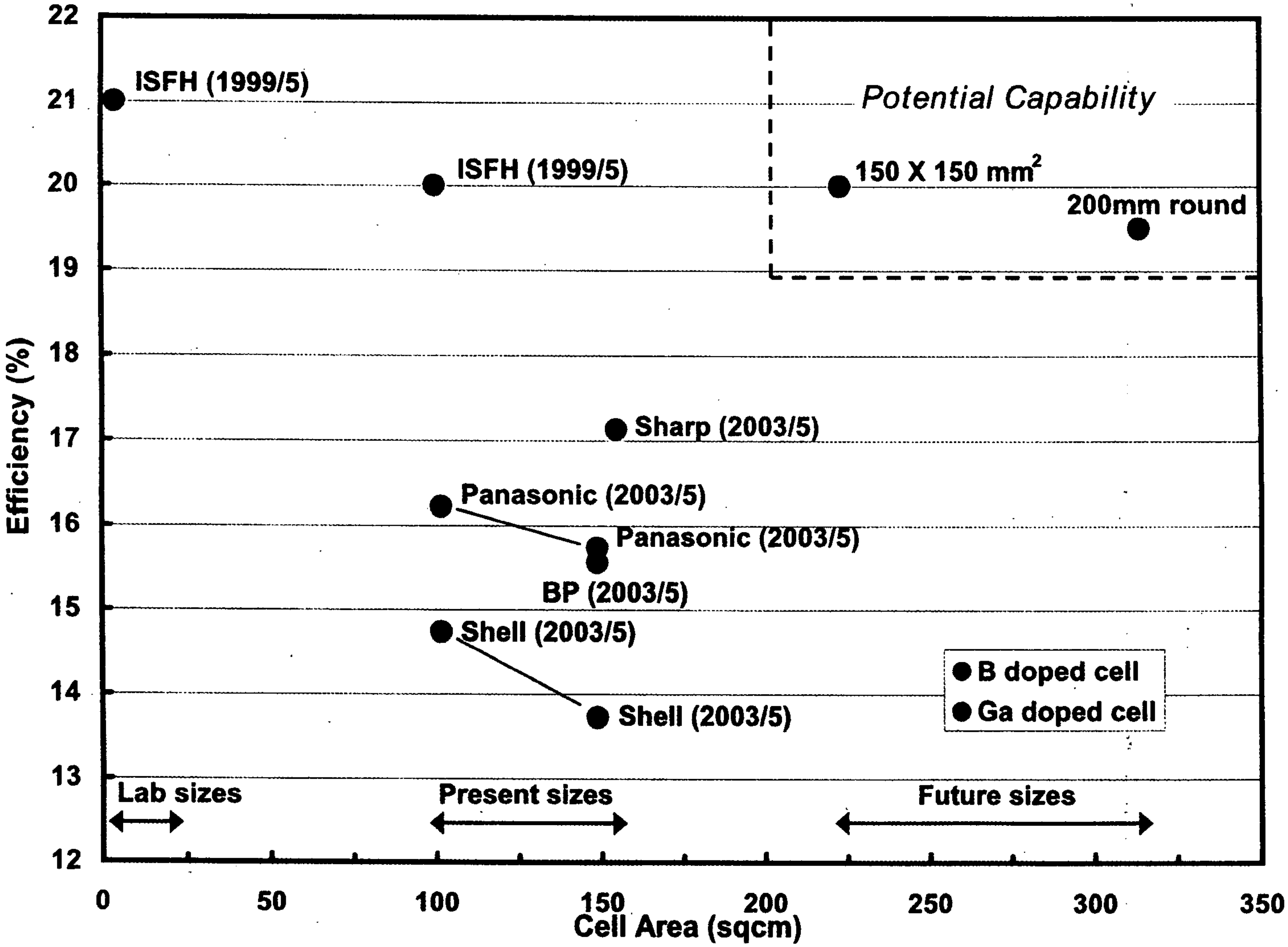
19. I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true; and further that these statements were made with the

knowledge that willful false statements and the like so made are punishable by fine and/or imprisonment under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing therefrom.

Date: February 10, 2004 Takao ABE

Takao Abe

Cell Area and Efficiency of Single Si Cells



Fraunhofer Institut
Solare Energiesysteme

The Fraunhofer ISE PV Charts:

Assessment of PV Device Performance

Edition

The Fraunhofer ISE PV-Charts are a compilation of certified solar cell data measured at the Fraunhofer ISE PV Calibration Laboratory. Not only world record cells are included in this list. It is rather intended to give a survey of the state of the art that is reached at various research- or industrial laboratories/ production lines. Therefore, high efficiency cells, but also emerging technologies - even of lower efficiency - will be listed, if they are of general interest.

INTRODUCTION

Continously, many new cells based on new materials or technological concepts are presented by both industry and research institutes. Efficiency and power are important factors for the assessment of these solar cells.
The Fraunhofer ISE PV Charts intend to give a survey of the state of the art that is reached at various research - or industrial laboratories and production lines. This service to the PV community combines easy comparability of new achievements and high precision.

STRUCTURE OF THE FRAUNHOFER ISE PV-CHARTS

The Fraunhofer ISE PV-Charts have been introduced at the IEEE PVSC, 1993, and the EC PVSEC, 1994.
They are open - everybody can provide samples and measurements are free of charge if the agreement for publication is given.
All samples have been provided directly by the corresponding laboratories. After the measurements have been communicated, these laboratories have given their agreement for publication.
The Fraunhofer ISE PV Charts are also available on the World Wide Web at the URL http:// www. ise. fhg. de/kallab/Welcome.html.
High precision measurements are an important prerequisite for device assessment. Even at an uncertainty level of only 2% (relative), the 'true' efficiency of a high efficiency cell of 24% will be anywhere between 23.5% and 24.5%. Often, the gain in efficiency as compared to previous results may be close to the measurement uncertainty rendering high precision measurements important for assessment.
Frequent interlab measurement intercomparisons have been used to testify the high measurement quality of the Fraunhofer ISE PV calibration laboratory.

HOW TO READ THE ISE PV CHARTS

The Fraunhofer ISE PV - Charts are divided into sections corresponding to important material groups - such as silicon (mono and multicrystalline), III-V materials (such as gallium-arsenide) and other single junction cells (such as the thin film materials amorphous silicon/germanium, cadmium telluride, copper indium diselenide). Two more sections represent specialised applications and cell design methods, such as concentrator solar cells and multijunction solar cells.

For each terrestrial solar cell we quote the efficiency at standard conditions (STC: irradiance 1000 W/m^2, cell test temperature 25°C, light spectrum AM 1.5 global). Data for concentrator cells deviate from this general rule in that efficiences are quoted for operation at the spectrum AM 1.5 direct, data for space solar cells are given for an irradiance of 1367 W/m^2 with a spectral distribution with respect to AM 0 WRL . Next to the efficiency, the measurement uncertainty U_{95} is given. With 95% confidence level, the cell's efficiency can be found in the interval $\eta \pm U_{95}$.
In addition to efficiency, the cell area (A, in cm^2) is an important factor: Large area solar cells tend to show lower efficiencies than small area cells of corresponding technology. Laboratory cells (denoted as L) usually are the best of a small quantity of cells, produced in equipment optimised to obtain highest efficiencies. Production cells (denoted as P) will also originate from the upper end of the manufacturers efficiency distribution. Nevertheless, the manufacturer will be able to produce 'similiar' cells in 'high' quantities.
The short circuit current density (j_{sc}),open circuit voltage (V_{oc}),fillfactor (FF) and the date of the measurement indicate additional important data on the solar cells.

Fraunhofer Institut Solare Energiesysteme

ISE PV-Charts

Edition 11 Update 1
Date: Jun 26th, 1998

silicon cells monocrystalline

$\eta \pm U_{95}$ [%]	Lab. Prod.	A [cm²]	Manufacturer	Remarks	j_{sc} [mA/cm²]	V_{oc} [V]	FF [%]	Identification	Date
23.5 ± 0.5	L	4.00	UNSW, Sydney, Aus	PERL- technology	40.8	0.704	81.9	UNW11/ZT-1-2E	11/94
23.3 ± 0.4	L	4.02	ISE, Freiburg, D	FZ-Si, LBSF process	41.3	0.700	80.6	161ISE/FB101-3c	09/96
23.3 ± 0.5	L	4.00	ISE, Freiburg, D	FZ-Si, LBSF process, 2 ARC	42.0	0.685	81.0	158ISE/FB99-4d	09/96
22.7 ± 0.4	L	4.02	ISE, Freiburg, D	FZ-Si MESC process (note 4)	40.5	0.696	80.3	162ISE/GEB2.8c	09/96
22.7 ± 0.4	P	21.10	Sun Power, Sunnyvale, USA rear contact	for 1996 World Solar Challenge	40.0	0.681	83.3	008SPR/9693	11/96
22.5 ± 0.5	L	20.64	ISE, Freiburg, D	FZ-Si, LBSF-process, cell for shingle modules designated area	40.4	0.693	80.4	ISE205/FB118-4a	05/98
22.0 ± 0.4	L	4.02	ISE, Freiburg, D	CZ-Si, LBSF process	41.8	0.680	77.2	169ISE/CB 24.1	11/96
21.6 ± 0.4	L	4.00	ISE, Freiburg, D	FZ-Si, random pyramids, PERC	39.6	0.676	80.7	ISE133/RPAL5.4a	03/96
21.5 ± 0.4	P	17.70	Sun Power, Sunnyvale, USA	cell type powering Honda's Dream solar car.	38.8	0.681	81.3	SPR3 / R2071	07/93
21.4 ± 0.4	L	21.10	ISE, Freiburg, D	LBSF/PERL- technology, FZ material	38.6	0.692	80.2	ISE82 / FB 27.4	10/93
21.3 ± 0.4	L	45.70	UNSW, Sydney, Aus	PERL- technology	39.2	0.695	78.1	UNW9 / H4621	08/93
21.1 ± 0.5	L	3.50	PSI, Villigen, CH	measured at 36°C and corrected to 25°C	38.3	0.677	81.4	PSI3/W102-5c	04/96
21.1 ± 0.5	L	3.90	ISFH, Emmerthal, D	FZ-Si MISn+p	40.5	0.666	78.0	013ISF/AM47/10	04/97
20.9 ± 0.4	L	4.00	ISFH, Emmerthal, D	FZ, single diff., random pyramids, mask evaporation	39.5	0.657	80.5	012ISF/AH4401B	11/96
20.8 ± 0.4	L	23.30	ASE, Heilbronn, D	FZ,space techn. random pyramids	39.8	0.648	80.8	ASH20/35/2	02/96
20.7 ± 0.4	L	3.90	IMEC, Leuven, B	WACKER substrate	39.0	0.668	79.7	IMC6 / 1192 SB	01/93
20.0 ± 0.4	L	3.90	ISFH, Hameln, D	FZ, single diffusion, random pyramids	36.6	0.675	80.9	ISF1/CH503d	07/95
19.4 ± 0.4	P	23.40	ASE, Heilbronn, D	CZ material, space production type cell	39.5	0.627	78.1	DAH1 / Nr.1	12/93
19.3 ± 0.5	L	12.00	ASE, Wedel, D	high efficiency technology, buried contacts	37.4	0.647	79.8	AEG9 / 6-13-3	04/89
19.2 ± 0.5	L	4.00	ANU/Samsung AIT AUS/KR	PESC, double phosph. diff Note 2	35.3	0.666	81.8	ANU1/EC7-1	01/96
19.1 ± 0.5	L	4.00	ANU/Samsung AIT AUS/KR	PESC, single phosph. diff. Note 2	35.5	0.662	81.3	ANU1/EC5-1	01/96
18.6 ± 0.4	L	4.10	ISFH, Emmerthal, D	MINP cell, mask free shallow angle evaporation	36.2	0.654	78.4	ISF9/MV37-9	04/96
18.5 ± 0.5	L	3.90	ISFH, Emmerthal, D	FZ-Si MIS-IL	39.3	0.615	76.7	ISF016/AM54/6	09/97
18.4 ± 0.4	L	25.00	SSG, München, D	FZ-material	37.8	0.653	74.7	SSG50/K37	05/95
18.3 ± 0.4	L	21.20	ISE, Freiburg, D	FZ, 2ARC, no texturing	35.2	0.661	78.7	ISE127/DJK19-1	01/96
18.3 ± 0.5	L	25.00	SSG, München, D	CZ-material	37.6	0.641	75.8	SSG49/K22	05/95
17.5 ± 0.4	P	100.50	ASE, Heilbronn, D	CZ material (FEW), n+pp+	37.2	0.612	76.6	DAH2 / 1A	09/93
17.1 ± 0.3	L	4.10	PSI, Villigen, CH	n- type emitter, cell thickness 215 µm (note 2)	31.4	0.672	81.3	PSI3 / W8-119CT	04/94
17.1 ± 0.4	L	89.80	IMEC, Leuven, B	Cz-Si, selective emitter, sreen-printed contacts	36.9	0.621	74.7	IMC019/Z735	06/98
17.1 ± 0.4	L	4.00	ISFH, Emmerthal, D	Truncated pyramid MIS-IL	35.5	0.639	75.5	ISFS/951001PrI	10/95
16.8 ± 0.4	L	105.00	SSG, München, D	CZ, screen printed BSF cell	35.0	0.621	77.0	SSG059#2	03/96
16.7 ± 0.3	P	142.90	BP Solar, E	high efficiency plant Madrid	34.6	0.614	78.6	BPS11 / TC 11	04/94
16.7 ± 0.3	L	95.10	IMEC, Leuven, B	Cz-Si, select. screen printed diffus. and metallisation	32.3	0.618	76.3	IMC014/2623F7	12/97
16.6 ± 0.3	L	4.00	LME/USP-INPE, Sao Paulo, BRA	FZ-Si	33.2	0.639	78.2	UPM004/N-7-2/LME	03/98
16.3 ± 0.3	L	4.10	PSI, Villigen, CH	n- type emitter, cell thickness 200 µm (note 2)	29.6	0.677	81.3	PSI3 / W8-20MC	04/94
15.8 ± 0.3	P	97.90	SSG, München, D	CZ material, 12 kW production, HEPCO	33.8	0.614	76.2	SSG22 / HEPC 1-2	12/93
15.7 ± 0.3	L	4.00	ISFH, Emmerthal, D	FZ-mat., MIS-IL, 300 µ 0.6 Ohm cm	35.6	0.595	74.4	ISF3/MIS-IL	08/95
15.6 ± 0.3	P	96.50	NAPS, Espoo, SF	CZ tri-grain material (note1)	33.9	0.613	75.0	NAP1/TC93	11/94
15.3 ± 0.3	L	100.40	ASE, Alzenau, D	CZ material	33.1	0.605	76.3	ASA4/AM801	11/94
15.3 ± 0.3	L	98.50	BP Solar, U.K.	BSF and ARC	32.9	0.605	76.7	BPS12/HE9	11/94
15.1 ± 0.3	L	4.00	ASE, Alzenau, D	MIS	32.3	0.617	75.5	NUK2 / KZ169	01/89
14.7 ± 0.3	L	1.00	MPI, Stuttgart, D	LPE base 16.8 µm	27.2	0.659	82.2	MPI7 / 9S3	10/92
14.5 ± 0.3	L	4.00	Univ. Konstanz, D	SIPOS	32.6	0.623	71.6	010UNK/S07174	12/96
14.4 ± 0.3	L	4.00	USP/LME-INPE,S.Paulo, BRA	FZ- Si, BSF, 1.0 Ohm cm	30.1	0.622	76.9	UPM1/ LME- S64	02/95
14.3 ± 0.3	P	100.90	ASE, Heilbronn, D	CZ-mat. Bayer Solar GmbH, n+p, no interconn. (note 1)	31.3	0.602	75.8	DAH12/F101-127	11/94
14.1 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "steel blue"	29.7	0.603	78.5	BPS17/B-5	05/95
14.0 ± 0.3	L	68.40	VIESH, Moscow, R		31.1	0.611	73.5	VIS3 / -	04/92
13.5 ± 0.3	P	103.00	BP Solar, U.K.	BSF, no ARC	30.1	0.599	75.2	BPS13/LE2	11/94
12.4 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "gold"	26.4	0.601	78.2	BPS15/G-13	05/95
12.2 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "magenta"	26.2	0.597	77.9	BPS16/M-21	05/95
12.1 ± 0.3	P	67.40	Saturn, Krasnodar, R	for module type BS55	26.7	0.610	74.3	SAT10/#2	07/95
11.5 ± 0.3	L	1.00	MPI, Stuttgart, D	LPE base 4.2 µm	21.4	0.662	81.1	MPIBMW-S4	12/92
11.2 ± 0.3	P	64.90	Saturn, Krasnodar, R	for module type BS50	24.8	0.597	76.0	SAT12	07/95

silicon cells multicrystalline

$\eta \pm U_{95}$ [%]	Lab. Prod.	A [cm²]	Manufacturer	Remarks	j_{sc} [mA/cm²]	V_{oc} [V]	FF [%]	Identification	Date
17.4 ± 0.4	L	21.20	ISE, Freiburg, D	Eurosolare, 2ARC, oxide passiv.	34.4	0.637	79.2	176ISE/C15-7	03/97
16.9 ± 0.4	L	21.20	ISE, Freiburg, D	Baysix material (Bayer ex Freiberg)	34.8	0.617	78.8	ISE202/CB29-7	03/98
16.8 ± 0.3	L	21.20	ISE, Freiburg, D	Baysix, 2ARC, no texturing	34.3	0.621	78.8	ISE130/DJK19-11	01/96
16.5 ± 0.3	L	4.00	IMEC, Leuven, B	POLIX material	33.5	0.638	77.4	IMC9PB1-4	01/94
16.5 ± 0.4	L	98.00	IMEC, Leuven, B	screen printed contacts, mechanically textured surface	35.5	0.612	75.7	IMC018/2	06/98
16.5 ± 0.3	L	3.90	ISFH, Emmerthal, D	Baysix, MISn+p cell, SiN passiv., no text.	33.5	0.634	77.6	ISF017/HNAM2	12/97
16.4 ± 0.3	L	98.00	ASE, Heilbronn, D	Baysix material, no interconnectors (note 1)	33.4	0.622	79.0	TFK45 / 214-34-2	11/92
16.3 ± 0.3	L	98.10	IMEC, Leuven, B	Baysix mat., screen printed contacts	34.5	0.624	75.9	IMC016/19	02/98
16.2 ± 0.3	L	4.00	ISE, Freiburg, D	Baysix material, no interconnectors (note 1)	33.3	0.632	76.8	ISE57 / MCB 3.2	01/93
16.0 ± 0.3	L	3.90	IMEC, Leuven, B	Eurosolare substrate	34.2	0.604	77.8	IMC5 / FSD2	01/93
15.9 ± 0.3	L	95.80	IMEC, Leuven, B	BAYSIX screen printed contacts	33.3	0.620	77.2	IMC13/Z446-B3	07/96
14.4 ± 0.3	L	25.00	SSG, München, D	Baysix material	30.9	0.612	76.2	SSG29 / G65	03/94
13.7 ± 0.3	L	100.20	ASE Alzenau, D; PIKLINGTON SOLAR INT.	cell recycled from module	31.5	0.599	72.4	ASA032/B10/12	05/98
13.7 ± 0.3	L	99.90	ASE, Heilbronn, D	Baysix material, n+p, screenprinted contacts	29.3	0.605	77.0	ASH3/PMC1-1	11/94
13.6 ± 0.3	L	92.20	IMEC, Leuven, B	Eurosolare substrate, no interconnectors (note 1)	31.1	0.595	73.5	IMC4/-	01/93
13.2 ± 0.3	L	4.00	Univ. Konstanz, D	SIPOS/Bayer SOPLIN	27.8	0.611	77.7	011UNK/S07D12	12/96
13.1 ± 0.3	P	100.20	ASE, Heilbronn, D	Baysix material, no interconnectors (note 1)	28.5	0.599	76.7	DAH13/B1C2-147	11/94
11.2 ± 0.3	L	4.10	MPI, Stuttgart, D	thin film LPE, base 26µm	24.2	0.643	72.1	MPI9 / 2GS	03/94
11.1 ± 0.3	L	4.00	Uni Konstanz	Bayer RGS material	28.4	0.538	72.4	014UNK/100.4d	07/97

PATENT APPLICATION

OIPE JC174 FEB 25 2004 PATENT & TRADEMARK OFFICE

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re the Application of

Takao ABE et al.

Application No.: 09/743,982

Filed: January 18, 2001

Group Art Unit: 1765

Examiner: M. Anderson

Docket No.: 108360

For: SILICON SINGLE CRYSTAL AND WAFER DOPED WITH GALLIUM AND METHOD FOR PRODUCING THEM

DECLARATION UNDER 37 C.F.R. §1.132

I, Lionel C. Kimerling, a citizen of the United States of America, hereby declare and state:

1. I have a degree in Electronic Materials which was conferred upon me by the Massachusetts Institute of Technology in Cambridge, Massachusetts in 1969.

2. I have been employed by the Massachusetts Institute of Technology since 1990 and I have had a total of 35 years of work and research experience in silicon semiconductor solar cell technology.

3. My memberships, publications and other qualifications are accurately described in the attached curriculum vitae.

4. I have reviewed the above-captioned patent application and the current claims therein.

5. I have reviewed J. Minahan et al., Irradiated Solar Cells Fabricated From Gallium-Doped/Boron-Doped FZ and CZ Silicon (Conf. Rec. IEEE Photovoltaic Spec. Conf. (1982) 16^{th}, 310-315); Wolf et al., Silicon Processing for the VLSI Era, Vol. 1: Processing Technology (Lattice Press, Sunset Beach, CA, USA pp. 1-35, 1986); and U.S. Patent

6,147,297 to Wettling et al. I am familiar with the level of skill in the art of silicon single crystal solar cells, both now and in 1999.

6. Prior to publication of Dr. Abe et al.'s invention in 1999, it was generally understood among those of ordinary skill in the art that, while large, boron-doped Czochralski silicon single crystals having small, generally central, areas of high conversion efficiency could be obtained, the overall conversion efficiency of solar cells (i.e., the conversion efficiency as defined at page 28 of the above-captioned patent application) made from doped silicon single crystals decreased with increased wafer size, in large part because of the increase in oxygen concentration that occurs with increased proximity to the outer portions of a Czochralski wafer, due to dissolution into the melt of quartz crucible layers during the quartz-crucible Czochralski crystal growth process. As discussed in the explanatory section on "How to Read the ISE PV Charts" of Fraunhofer ISE PV Charts: Assessment of PV Device Performance, 11^{th} ed. (1998), *silicon cells monocrystalline*, cell area and efficiency were both important factors in evaluating a solar cell, since "[l]arge area solar cells tend to show lower efficiencies than small area cells of corresponding technology."

7. It was generally understood at that time that, in order to improve solar cell semiconductors, one must move away from silicon single crystal systems to multi-crystalline systems, adjust boron content or oxygen content of silicon single crystal systems, or move away from the Czochralski process altogether for silicon single crystal systems, toward, for example, the Floating Zone process, which involves higher production costs and is process-limited to producing small-diameter crystals and thus small-diameter wafers.

8. In addition, while it was known that electronics-grade crystals could be formed with diameters of four inches or more, it was not known that solar-cell-grade, gallium-doped Czochralski silicon single crystals could be formed having diameters of four or more inches

with high overall conversion efficiency and little or no photo-degradation effects, at the low cost of the quartz-crucible Czochralski process.

9. While it was known that gallium could be used as a dopant in solar-cell-grade silicon single crystals, it was not known that a specific concentration of gallium or a gallium-induced resistivity range in the range of 5 Ω·cm to 0.1 Ω·cm would produce a peak in conversion efficiency superior to that found in boron-doped silicon single crystals of similar sizes and resistivities, and with little or no photo-degradation.

10. That such a peak in overall conversion efficiency for large diameter crystals with high reliability and low photo-degradation effects and long minority carrier lifetimes could be achieved in combination by selecting the conditions recited in the claims was unknown and unexpected in the art. This advance was addressed in the context of Dr. Abe et al.'s invention in Light Degradation and Control of Low-Resistivity CZ-Si Solar Cells, *Technical Digest of the International PVSEC-11*, 1999, pp. 553-556. For this paper, Dr. Abe et al. were honored with the Special Paper Award of the 11th International Photovoltaic Science and Engineering Conference.

11. It was not known in 1999 prior to publication of Dr. Abe et al.'s invention that quartz-crucible Czochralski solar-cell-grade crystals, with gallium as the dopant that controls the resistivity of the crystal, in the specific resistivity in the range of 0.1 to 5 Ω·cm, or the specific gallium concentration in the range of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, could be formed with diameters of four inches or more and still have conversion efficiencies and lifetimes at the levels achieved by Dr. Abe et al.'s invention as defined in the current claims of the above-captioned patent application. The Fraunhofer ISE PV Charts confirm the fact that the highest conversion efficiency that had been obtained in a large-size Czochralski silicon single crystal solar cell was about 17.5%. The Fraunhofer ISE PV Charts list certified

solar cell data measured at the Fraunhofer ISE. For each silicon single crystal solar cell tested by Fraunhofer ISE, the chart lists the measured conversion efficiency at standard conditions with the accompanying measurement uncertainty, whether the solar cell is a laboratory or production cell, the cell area, the manufacturer and remarks, along with some additional properties and data, such as the testing date. As discussed in the explanatory section on "How to Read the ISE PV Charts," cell area and efficiency were both considered important factors in evaluating a solar cell because "[l]arge area solar cells tend to show lower efficiencies than small area cells of corresponding technology."

12. A 100.50 cm^2 Czochralski silicon single crystal solar cell having a conversion efficiency of only about 17.5% is reported as the twenty-seventh entry of the *silicon cells monocrystalline* section of the Fraunhofer ISE PV Charts. I believe this was a boron-doped solar cell. All of the other about 100 cm^2 or larger cells had even lower conversion efficiencies.

13. As can be seen from comparing the Fraunhofer ISE PV Charts to the data in the specification of the above-captioned patent application, the claimed invention has the potential to achieve a previously unaccomplished feat: producing a solar cell from a silicon single crystal having a high oxygen concentration due to quartz-crucible dissolution during manufacture by the quartz-crucible Czochralski method, a large area (such as achieved with the claimed diameter of at least four inches), using gallium as the dopant to control resistivity, and capable of having a conversion efficiency of over 20% that can be maintained without significant photo-degradation. The high oxygen content further endows the silicon single crystal with significant benefits, including improved wafer strength and resistance to deformation, both of which contribute to reduced degradation during mechanical processing, especially in large diameter wafers such as those having a diameter of four inches or more. That is, the high oxygen content resulting from quartz crucible dissolution during the

Czochralski crystal growth process allows the wafer to maintain its mechanical integrity even under conditions, such as at the high temperatures used in cell processing, in which the weight of the wafer itself and the mechanical leverage imposed by its diameter might otherwise result in wafer deformation or compromised mechanical properties.

14. Similarly, it was not known in 1999 prior to the publication of Dr. Abe et al.'s invention that gallium could be used as a dopant in solar-cell-grade silicon single crystals having diameters of four inches or more with improved overall conversion efficiency and substantially no photo-degradation.

15. Prior to publication of Dr. Abe et al.'s invention in 1999, it was unexpected to find the peak in conversion efficiencies described in the specification of the above-captioned patent application without the photo-degradation that degrades boron-doped wafer conversion efficiencies at corresponding resistivities, for the specific resistivity in the range of 0.1 to 5 $\Omega\cdot$cm, or the specific gallium concentration in the range of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3.

16. Prior to publication of Dr. Abe et al.'s invention in 1999, one of ordinary skill in the art would have found no suggestion or motivation in Minahan, Wolf or Wettling to combine or modify these references to achieve the highly efficient, low-cost, long-lifetime, large-diameter silicon single crystal or wafer for a solar cell by the combination of producing the crystal according to the Czochralski method with gallium as a dopant that controls resistivity of the crystal, using the gallium in an amount that produces a resistivity of 0.1 to 5 $\Omega\cdot$cm, or a gallium concentration of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, forming the single crystal with a diameter of four inches or more; and using the single crystal for a solar cell.

17. One of ordinary skill in the art would not have been motivated to modify Minahan to provide Czochralski silicon single crystal wafers having a gallium concentration in the range of from 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, or a resistivity in the range of 5 Ω·cm to 0.1 Ω·cm based on Figure 22 of Wolf, at least because boron-doped quartz-crucible Czochralski silicon single crystal solar cells were known in the art to undergo significant photo-degradation, due in part to the high oxygen content caused by contact between the quartz crucible and the melt during Czochralski crystal growth and boron-oxygen pairing, at boron-induced resistivities within the range of 5 Ω·cm to 0.1 Ω·cm.

18. One of ordinary skill in the art would not have been motivated by Minahan, alone or in combination with any other references, to provide low-cost, long-lifetime, large-diameter, solar-cell-grade, gallium-doped Czochralski silicon single crystals or wafers having a gallium concentration in the range of from 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, or a resistivity in the range of 5 Ω·cm to 0.1 Ω·cm and with high overall conversion efficiencies and little or no photo-degradation effects, at least because Minahan is directed to electron beam irradiation tolerance, a phenomenon entirely different from and not relevant to photo-degradation effects.

19. Neither Minahan nor Wolf nor Wettling would have suggested to one of ordinary skill in the art in 1999 prior to publication of Dr. Abe et al.'s invention that there may be any advantage in producing doped Czochralski silicon single crystals like those obtained by the combination of producing the crystal according to the Czochralski method with gallium as a dopant that controls resistivity of the crystal, using the gallium in an amount that produces a resistivity of 0.1 to 5 Ω·cm, or a gallium concentration of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, forming the single crystal with a diameter of four inches or more, and using the single crystal for a solar cell with this combination of features.

20. It is my opinion that one of ordinary skill in the art would not have been motivated to combine Minahan and Wolf to produce larger crystals having more surface area for solar cell formation with any reasonable expectation of success, for at least the reason that increasing the size of the silicon single crystal was understood in the art to increase the problems associated with oxygen contamination caused by melt-contact quartz crucible dissolution in the Czochralski process, such as photo-degradation, as discussed above, and Minahan and Wolf do not address how to avoid such problems in Czochralski crystals.

21. That such highly efficient, low-cost, long-lifetime silicon single crystals for solar cells could be produced by the combination of producing the crystal according to the Czochralski method with gallium as a dopant that controls resistivity of the crystal, using the gallium in an amount that produces a resistivity of 0.1 to 5 $\Omega \cdot cm$, or a gallium concentration of 5×10^{17} atoms/cm^3 to 3×10^{15} atoms/cm^3, forming the single crystal with a diameter of four inches or more, and using the single crystal for a solar cell with this combination of features was surprising because increasing the size of the silicon single crystal was understood in the art to increase the problems associated with oxygen contamination.

22. In 1999 prior to publication of Dr. Abe et al.'s invention, there existed a long-felt need in the art for a highly efficient, low-cost, long-lifetime silicon single crystal solar cell. After about 50 years of silicon semiconductor solar cell development, researchers were still attempting to maximize the size and conversion efficiencies of solar cells, and had not been able to achieve highly efficient, low-cost, long-lifetime silicon single crystals for solar cells with high overall conversion efficiencies, little or no photo-degradation, and with a diameter of four inches or more. When, for the first time, a low-cost solar cell having a diameter of at least four inches, capable of a conversion efficiency of 20% or more, without significant lowering of the conversion efficiency by photo-degradation, was formed by

Dr. Abe et al., researchers in the art saw the concrete potential for commercially viable solar power and acknowledged that advancement in the art with their acclaim and with the Special Paper Award of the 11th International Photovoltaic Science and Engineering Conference.

23. All statements made herein of my own knowledge are true, and all statements made on information and belief are believed to be true; and further these statements were made with the knowledge that willful false statements and the like so made are punishable by fine and/or imprisonment under Section 1001 of Title 18 of the United States Code, and that such willful false statements may jeopardize the validity of the application or any patent issuing therefrom.

Date: 2-21-04

Lionel C Kimerling

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CURRICULUM VITAE

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EDUCATION

Massachusetts Institute of Technology	S.B., 1965	Metallurgy
Massachusetts Institute of Technology	Ph.D., 1969	Materials Science

PROFESSIONAL EMPLOYMENT

Massachusetts Institute of Technology:
- Thomas Lord Professor of Materials Science and Engineering, 1990-present
- Director, Materials Processing Center, 1993-present

AT & T Bell Laboratories:
- Member, Technical Staff, Materials Physics Research Department, 1972-1981
- Head, Materials Physics Research Department, 1981-1990

Air Force Cambridge Research Laboratories:
- Captain U.S.A.F., Solid State Sciences Laboratory, 1969-1972

EDUCATIONAL ACTIVITIES

Professor of Electronic Materials, Adjunct, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1984-1990
Professor of Physics, Adjunct, Physics Department, Lehigh University, Bethlehem, Pennsylvania, 1977-1986
Visiting Fellow, Institute for the Study of Defects in Solids, SUNY-Albany, 1975-1977
Lecturer, Technion University, Haifa, Israel, 1976
Lecturer, Aarhus University, Aarhus, Denmark, 1974
Visiting Committee, Fairchild Laboratory for Solid State Studies, Lehigh University

AWARDS AND DISTINCTIONS

TMS Fellow, 2000
John Bardeen Award, TMS, 1999
Humbolt Senior Scientist Award, 1997
MIT's Perkins Award for Excellence in Graduate Advising, 1996
Electronics Division Award, ECS, 1995
Fellow of the American Association for the Advancement of Science, 1992
John E. Dorn Memorial Lecturer, 1992
Fellow of the American Physical Society, 1987
Welch Foundation Lecture, 1979

PROFESSIONAL ACTIVITIES

Journal of Electronic Materials: Chairman, Editorial Board, 1986-present.
The Minerals, Metals and Materials Society (TMS):
- President, Foundation Board of Trustees, 1998-2002
- Member-At-Large, Foundation Board of Trustees, 1998-2002
- President, 1994
- Vice-President, 1993
- Director, Electronic, Magnetic and Photonic Materials Division, 1989-1993.

National Center for Photovoltaics Advisory Board
Electronic Device Materials Committee (TMS): Chairman, 1986-1989.
Electronic Materials Committee (TMS):
- Member-at-Large, 1982-present
- Secretary, 1980-1982
- Assistant Secretary, 1978-1980
- Member, 1977-present

AIME: Trustee, 1994-present
National Materials Advisory Board:
- Member, 1992-present
- Committee on "High Temperature Semiconductor Materials," 1994.
- Committee on "On-Line Control of Metal Processing," 1987.

SEMATECH:
- Wafer Defect Engineering Task Force, Silicon Council, 1993-present..

Organizer, Chairman, Proceedings Editor:
- 13th International Conference on Defects in Semiconductors, Coronado, California, 1984.
- "Defects in Silicon," 163rd Annual Electrochemical Society Meeting, New York, 1985.
- "Oxygen in Silicon," 114th Annual TMS/AIME Meeting, New York, 1985.

Organizer, Chairman: "Defects in Semiconductors," "Laser and Electronic Beam Processing," "Low Temperature Processing of Semiconductor," "Silicon Photonics," "New Issues in Silicon Materials for VLSI," and "Materials Interfaces" Annual Electronic Materials Conference, TMS, 1978-present.
International Advisory Committee: 10th, 11th, 12th, 13th, 14th, 15th, 16th, 17th, 18th, 19th, and 20th International Conference on Defects in Semiconductors 1978, 1980, 1982, 1984, 1986, 1988, 1991, 1993, 1995, 1997, 1999.
International Advisory Committee: International Conference on Defect Control in Semiconductors, Yokohama, 1989.

HONORARY PROFESSIONAL SOCIETIES

Phi Lambda Upsilon
Sigma Xi

PROFESSIONAL SOCIETIES

American Association for the Advancement of Science
American Physical Society
American Society for Metals
Materials Research Society
The Electrochemical Society
The Minerals, Metals, and Materials Society
Electron Device Society, IEEE

PUBLICATIONS

1. L. C. Kimerling, "Initial Investigations into the Fabrication of a Microelectronic Magnetic-Core Logic Element," S.B. Thesis, MIT, 1965.

2. L. C. Kimerling, "Compensation of Germanium by Radiation Defects," Ph.D. Thesis, MIT, 1969.

3. L. C. Kimerling, L. B. Golovin, and H. C. Gatos, "Germanium Radiation Detectors Compensated by Irradiation Defects," *Proceedings of the IEEE, Ottawa, CANADA*, **57** 208 (1969).

4. H. M. DeAngelis, C. P. Carnes and L. C. Kimerling, "Isochronal Annealing of Electron-Irradiated, P-Doped Silicon," *Bulletin of the American Physics Society* **15** 397 (1970).

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7. P. J. Drevinsky and L. C. Kimerling, "Carrier Removal in Li-Doped Silicon Irradiated with 5-MeV Neutrons," *Bulletin of the American Physics Society* **16** 499 (1971).

8. L. C. Kimerling and C. P. Carnes, "Annealing of Electron-Irradiated, N-Type Silicon: Illumination and Fluence Dependence," *Journal of Applied Physics* **42** 3548 (1971).

9. L. C. Kimerling and P. J. Drevinsky, "Carrier Removal Effects in Neutron-Irradiated, Lithium-Doped Silicon," *IEEE Transactions in Nuclear Science* **NS-18** 60 (1971).

10. L. C. Kimerling, "Radiation Effects in n-Type Silicon Semiconductors," *Proceedings of the AFSC Science and Engineering Symposium*, Dayton, OH, 569 (1971).

11. T. J. Magee, J. J. Comer, and L. C. Kimerling, "Lithium Precipitation in Silicon," *Proceedings of the 29th Annual Conference of the Electron Microscopy Society of America*, Boston, MA, 150 (1971).

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14. J. W. Diebold, H. M. DeAngelis, and L. C. Kimerling, "Specific Observations of Radiation Effects in Semiconductors by Junction-Capacitance Techniques," in Radiation Damage and Defects in Semiconductors, (Institute of Physics, London, 1973) p. 295.

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16. L. C. Kimerling, "On the Role of Defect Charge State in the Stability of Point Defects in Silicon," *Bulletin of the American Physics Society* **19** 210 (1973).

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20. L. C. Kimerling and J. M. Poate, "Lattice Defects in Ion Implanted Semiconductors," in Lattice Defects in Semiconductor (Institute of Physics, London, 1975) p. 126. INVITED

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23. L. C. Kimerling and D. V. Lang, "The Influence of e-h Recombination on Defect Stability in Semiconductors," *Bulletin of the American Physics Society* **20** 317 (1975).

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31. L. C. Kimerling, H. J. Leamy, and G. E. Smith, "Healing Radiation Defects in Semiconductors," U. S. Patent No. 4,328,694.

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33. D. V. Lang and L. C. Kimerling, "Observation of Athermal Defect Annealing in GaP," *Applied Physics Letters* **28** 248 (1976).

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24% efficient silicon solar cells

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Significant improvements in silicon solar cell performance are reported using an improved high-efficiency silicon solar cell structure. This structure overcomes deficiencies in an earlier structure by locally diffusing boron into contact areas at the rear of the cells. Terrestrial energy conversion efficiencies up to 24% are reported for silicon cells for the first time. Air Mass 0 efficiencies lie in the 20–21% range, the first silicon cells to exceed 20% efficiency under space illumination.

Passivated emitter and rear cells (PERC cells)[1-3] have recently demonstrated energy conversion efficiency up to 23.2% under standard terrestrial test conditions (Air Mass 1.5 global radiation, ASTM E892 spectrum, 25 °C). These PERC cells have very high open-circuit voltage (V_{oc}) and short-circuit current density (J_{sc}) due to very low recombination rates in the bulk and at front and rear surfaces.[2] The rear ohmic contact areas, formed by intimate aluminum-silicon contact, are the only areas left unpassivated. The effect of recombination in these areas is minimized by separating these contact areas by a distance much larger than the thickness of the silicon substrate. The disadvantage of this large separation is that PERC cells have relatively low fill factors due to lateral resistance loss in the substrate. The aluminum-silicon contact not only has a high contact resistance, but also has noticeable rectifying properties when the substrate resistivity becomes higher than 0.5 Ω cm. This further constrains cell design.

All above disadvantages are eliminated in the passivated emitter, rear locally diffused (PERL) cell structure shown in Fig. 1. The main difference from the earlier PERC cell is the local diffusion of boron in rear contact areas. This reduces the effective recombination rate at the rear contacts by suppressing minority-carrier concentrations in these regions. Hence, it is possible to reduce the spacing of the rear contact points to decrease the cell lateral series resistance, giving much higher fill factors. The reduced recombination rates at the rear contact also improve both V_{oc} and J_{sc}, as well as allowing substrates of resistivity above 0.5 Ω cm to be used.

Although the potential advantages of diffusing these contact regions have been known for some time, the difficulty has been to find conditions which allow boron diffusion without lowering the exceptionally high bulk carrier lifetimes demonstrated in PERC cells. Initial boron diffusion experiments using "solid-source" or "spin-on" dopant sources[4] showed a large decrease of the carrier lifetime after boron diffusion. Cells displayed both lower V_{oc} and J_{sc}. This led to the investigation of BBr_3 liquid dopant source. The advantage of this liquid source is that it is compatible with the trichloroethane (TCA) based processing which was an important contributor to the high performance of the earlier PERC cells.[1]

To investigate lifetime degradation during diffusion from BBr_3 liquid source, 100 Ω cm, 280-μm-thick, double-side polished, float zone wafers were boron diffused over the entire front and rear surfaces under different diffusion conditions. They were then dipped in HF. A microwave based, conductivity decay lifetime tester[5] was used to measure carrier lifetime. The measured lifetime is actually an effective lifetime which includes recombination effects in the bulk and at the surfaces. The HF dip prior to testing reproducibly lowers the surface recombination component.[6] Such measurements showed that it was possible to obtain high effective carrier lifetimes (greater than 1 ms) under a range of diffusion conditions using the liquid BBr_3 source.

In actual cells, diffusing boron only into the localized contact regions as shown in Fig. 1 decreases recombination in these diffused regions. The boron dopant sheet resistivity for PERL cells was relatively low at around 20 Ω/□ to passivate the rear metal-silicon contact.[7] Boron was deposited at 900 °C for 15 min followed by drive-in at 1070 °C for 2 h. Other processing conditions were similar to those reported elsewhere.[1-3]

The new PERL cells have been fabricated on substrates of 0.5–100 Ω cm resistivity. The rear contact spacing was decreased to the 250–500 μm range rather than the 2 mm spacing of earlier PERC cells.[2] The locally diffused regions at the rear had a diameter of 30–100 μm. The metal contact windows with diameters of 10–50 μm were aligned

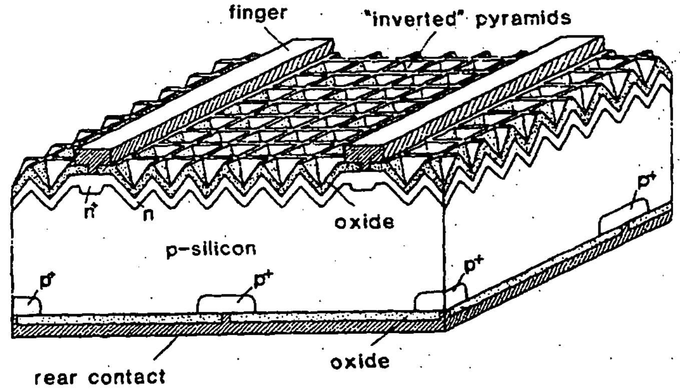

FIG. 1. Passivated emitter, rear locally diffused (PERL) solar cell.

TABLE I. Output parameters of high performance 4 cm^2 PERL silicon solar cell as measured by Sandia National Laboratories at 25 °C. AM1.5 measurements are relative to NASA calibrated reference cell Y49 under the ASTM E892 Global AM1.5 spectrum (100 mW/cm^2). AM0 measurements of J_{sc} are relative to NASA aircraft-calibrated PERC cell A142R, with V_{oc} and fill factor adjusted from the AM1.5 data using J_{sc} dependences measured for previous cells of this type. A solar constant of 137.2 mW/cm^2 was used in the efficiency calculation, giving a more conservative result than alternative values of 136.7 and 135.3 mW/cm^2 sometimes used for such calculations.

Spectrum	V_{oc} (mV)	J_{sc} (mA/cm^2)	Fill factor (%)	Efficiency (%)
AM1.5	696	42.9	81.0	24.2
AM0	701	50.5	80.5	20.8

to the center of these diffused areas. The closer spacing of the contact points greatly decreased the bulk resistance of the cell.

Cells fabricated with the improved boron diffusion conditions on both 0.5 and 2 Ω cm substrates have demonstrated energy conversion efficiency in the 23–24% range under standard terrestrial test conditions (Global AM1.5, ASTM E892 spectrum, 25 °C), as independently measured at both Sandia National Laboratories and the Solar Energy Research Institute. The output parameters of the highest efficiency device fabricated to data are shown in Table I. The measured efficiency of 24.2% is much higher than the highest previously reported for a silicon cell under these conditions of 23.2%.[3] Under AM0 radiation, efficiency in the 20–21% range has been measured at both the above laboratories and at NASA-Lewis Research Center. These are the first silicon cells to exceed 20% efficiency under AM0 testing. J_{sc} above 49 mA/cm^2 is measured for 0.5 Ω cm substrates under this spectrum, with values above 50 mA/cm^2 demonstrated by the 2 Ω cm substrates.

The main contributor to this exceptionally high J_{sc} is the high internal quantum efficiency of these cells. For the 2 Ω cm substrates, virtually every photon absorbed in silicon by electron-hole pair generation contributes to J_{sc}. This is demonstrated in Fig. 2 which shows the experimental internal quantum efficiency of the cell of Table I, together with the hemispherical reflection from this cell (the latter includes reflection from the top contact fingers). The measured internal quantum efficiency is 100%, to measurement accuracy, from 350 to 1050 nm. At longer wavelengths this efficiency decreases. The decrease is attributed to those photon absorption processes that compete directly with electron-hole pair generation for weakly absorbed photons. For the present cells, the most important of these is absorption in the rear metal reflector, although free-carrier absorption in the silicon is a more fundamental process of this type.

Also shown in Fig. 2 is the calculated internal quantum efficiency approximated by

$$\mathrm{QE}=\frac{\alpha}{\alpha+\alpha_{fc}+(1-R)/(2^*W^*\mathrm{PL})} \quad (1)$$

at wavelengths where α, the absorption coefficient of undoped silicon (e.g., Appendix C of Ref. 7), is small. α_{fc} is

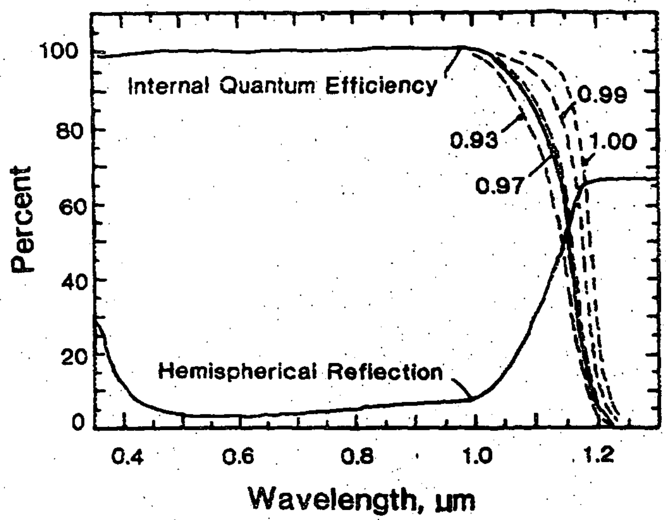

FIG. 2. Internal quantum efficiency and hemispherical reflectance (including that from metal fingers) for a high performance PERL silicon solar cell. Also shown as dashed lines are the results from theoretical calculations of the internal quantum efficiency for the different reflectivities of the cell rear surface indicated.

the free-carrier absorption coefficient. It has components from both the bulk of the cell and from the diffused regions. Its value can be estimated from the results of Schmid[8] as $3\times10^{-18}\lambda^2\overline{c}\,\mathrm{cm}^{-1}$, where λ is wavelength in μm and $\overline{c}$ is the average doping level in the cell in cm^{-3}. For the present cells, $\overline{c}$ was estimated as $1.7\times10^{16}\ \mathrm{cm}^{-3}$. This is over twice the substrate doping level since this value is augmented by the higher carrier concentrations in the diffused regions. PL is a path-length enhancement factor which takes into account the oblique passage of light across the wafer. A value of 1.35 was assigned in the present calculations [1/cos(45.5°)]. The angle of 45.5° corresponds to the most important initial double passage across the wafer, although different angles would apply for subsequent passes.

This analysis suggests that the main mechanism for improving the internal quantum efficiency of the cell is to improve the rear surface reflectivity, R, which presently appears to be about 97%. Ultimately, this efficiency will be limited by free-carrier absorption, at least at cell operating voltages.[7] The *external* quantum efficiency also depends on the reflection from the cell, which approaches a value of 67% at long wavelengths. Ray tracing shows that most of the light reflected at these wavelengths arises from light escaping after one "double pass" across the cell.[9]

Improving the cell's light-trapping scheme by incorporating pyramids on both top and rear surfaces[9] or by tilting the top surface pyramids[10] would decrease this reflection. The latter is the preferred option since the former would involve multiple bounces of light on some rear reflections, reducing the effective rear reflectivity and hence the internal quantum efficiency (Fig. 2).

The most direct route to improvement of the present devices, however, lies in reducing resistive losses in the cell to increase cell fill factor. Fill factors in the 83–84% range appear feasible. Numerical values for the limiting V_{oc} of silicon cells are still uncertain.[7] It appears as if values as

high as 740 mV should be feasible in thinned cells, without appreciable loss in J_{sc}. Silicon cell efficiency of 26% therefore appears attainable.

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Fraunhofer Institut
Solare Energiesysteme

The Fraunhofer ISE PV Charts:

Assessment of PV Device Performance

Edition

The Fraunhofer ISE PV-Charts are a compilation of certified solar cell data measured at the Fraunhofer ISE PV Calibration Laboratory. Not only world record cells are included in this list. It is rather intended to give a survey of the state of the art that is reached at various research- or industrial laboratories/ production lines. Therefore, high efficiency cells, but also emerging technologies - even of lower efficiency - will be listed, if they are of general interest.

INTRODUCTION

Continously, many new cells based on new materials or technological concepts are presented by both industry and research institutes. Efficiency and power are important factors for the assessment of these solar cells.

The Fraunhofer ISE PV Charts intend to give a survey of the state of the art that is reached at various research - or industrial laboratories and production lines. This service to the PV community combines easy comparability of new achievements and high precision.

STRUCTURE OF THE FRAUNHOFER ISE PV-CHARTS

The Fraunhofer ISE PV-Charts have been introduced at the IEEE PVSC, 1993, and the EC PVSEC, 1994.

They are open - everybody can provide samples and measurements are free of charge if the agreement for publication is given.

All samples have been provided directly by the corresponding laboratories. After the measurements have been communicated, these laboratories have given their agreement for publication.

The Fraunhofer ISE PV Charts are also available on the World Wide Web at the URL http:// www. ise. fhg. de/kallab/Welcome.html.

High precision measurements are an important prerequisite for device assessment. Even at an uncertainty level of only 2% (relative), the 'true' efficiency of a high efficiency cell of 24% will be anywhere between 23.5% and 24.5%. Often, the gain in efficiency as compared to previous results may be close to the measurement uncertainty rendering high precision measurements important for assessment.

Frequent interlab measurement intercomparisons have been used to testify the high measurement quality of the Fraunhofer ISE PV calibration laboratory.

HOW TO READ THE ISE PV CHARTS

The Fraunhofer ISE PV - Charts are divided into sections corresponding to important material groups - such as silicon (mono and multicrystalline), III-V materials (such as gallium-arsenide) and other single junction cells (such as the thin film materials amorphous silicon/germanium, cadmium telluride, copper indium diselenide). Two more sections represent specialised applications and cell design methods, such as concentrator solar cells and multijunction solar cells.

For each terrestrial solar cell we quote the efficiency at standard conditions (STC: irradiance 1000 W/m^2, cell test temperature 25°C, light spectrum AM 1.5 global). Data for concentrator cells deviate from this general rule in that efficiences are quoted for operation at the spectrum AM 1.5 direct, data for space solar cells are given for an irradiance of 1367 W/m^2 with a spectral distribution with respect to AM 0 WRL . Next to the efficiency, the measurement uncertainty U_{95} is given. With 95% confidence level, the cell's efficiency can be found in the interval $\eta \pm U_{95}$.

In addition to efficiency, the cell area (A, in cm^2) is an important factor: Large area solar cells tend to show lower efficiencies than small area cells of corresponding technology. Laboratory cells (denoted as L) usually are the best of a small quantity of cells, produced in equipment optimised to obtain highest efficiencies. Production cells (denoted as P) will also originate from the upper end of the manufacturers efficiency distribution. Nevertheless, the manufacturer will be able to produce 'similiar' cells in 'high' quantities.

The short circuit current density (j_{sc}),open circuit voltage (V_{oc}),fillfactor (FF) and the date of the measurement indicate additional important data on the solar cells.

Fraunhofer Institut Solare Energiesysteme

ISE PV-Charts

Edition 11 Update 1
Date: Jun 26th, 1998

silicon cells monocrystalline

$\eta \pm U_{95}$ [%]	Lab. Prod.	A [cm²]	Manufacturer	Remarks	j_{sc} [mA/cm²]	V_{oc} [V]	FF [%]	Identification	Date
23.5 ± 0.5	L	4.00	UNSW, Sydney, Aus	PERL- technology	40.8	0.704	81.9	UNW11/ZT-1-2E	11/94
23.3 ± 0.4	L	4.02	ISE, Freiburg, D	FZ-Si, LBSF process	41.3	0.700	80.6	161ISE/FB101-3c	09/96
23.3 ± 0.5	L	4.00	ISE, Freiburg, D	FZ-Si, LBSF process, 2 ARC	42.0	0.685	81.0	158ISE/FB99-4d	09/96
22.7 ± 0.4	L	4.02	ISE, Freiburg, D	FZ-Si MESC process (note 4)	40.5	0.696	80.3	162ISE/GEB2.8c	09/96
22.7 ± 0.4	P	21.10	Sun Power, Sunnyvale, USA rear contact	for 1996 World Solar Challenge	40.0	0.681	83.3	008SPR/9693	11/96
22.5 ± 0.5	L	20.64	ISE, Freiburg, D	FZ-Si, LBSF-process, cell for shingle modules designated area	40.4	0.693	80.4	ISE205/FB118-4a	05/98
22.0 ± 0.4	L	4.02	ISE, Freiburg, D	CZ-Si, LBSF process	41.8	0.680	77.2	169ISE/CB 24.1	11/96
21.6 ± 0.4	L	4.00	ISE, Freiburg, D	FZ-Si, random pyramids, PERC	39.6	0.676	80.7	ISE133/RPAL5.4a	03/96
21.5 ± 0.4	P	17.70	Sun Power, Sunnyvale, USA	cell type powering Honda's Dream solar car.	38.8	0.681	81.3	SPR3 / R2071	07/93
21.4 ± 0.4	L	21.10	ISE, Freiburg, D	LBSF/PERL- technology, FZ material	38.6	0.692	80.2	ISE82 / FB 27.4	10/93
21.3 ± 0.4	L	45.70	UNSW, Sydney, Aus	PERL- technology	39.2	0.695	78.1	UNW9 / H4621	08/93
21.1 ± 0.5	L	3.50	PSI, Villigen, CH	measured at 36°C and corrected to 25°C	38.3	0.677	81.4	PSI3/W102-5c	04/96
21.1 ± 0.5	L	3.90	ISFH, Emmerthal, D	FZ-Si MISn+p	40.5	0.666	78.0	013ISF/AM47/10	04/97
20.9 ± 0.4	L	4.00	ISFH, Emmerthal, D	FZ, single diff., random pyramids, mask evaporation	39.5	0.657	80.5	012ISF/AH4401B	11/96
20.8 ± 0.4	L	23.30	ASE, Heilbronn, D	FZ,space techn. random pyramids	39.8	0.648	80.8	ASH20/35/2	02/96
20.7 ± 0.4	L	3.90	IMEC, Leuven, B	WACKER substrate	39.0	0.668	79.7	IMC6 / 1192 SB	01/93
20.0 ± 0.4	L	3.90	ISFH, Hameln, D	FZ, single diffusion, random pyramids	36.6	0.675	80.9	ISF1/CH503d	07/95
19.4 ± 0.4	P	23.40	ASE, Heilbronn, D	CZ material, space production type cell	39.5	0.627	78.1	DAH1 / Nr.1	12/93
19.3 ± 0.5	L	12.00	ASE, Wedel, D	high efficiency technology, buried contacts	37.4	0.647	79.8	AEG9 / 6-13-3	04/89
19.2 ± 0.5	L	4.00	ANU/Samsung AIT AUS/KR	PESC, double phosph. diff Note 2	35.3	0.666	81.8	ANU1/EC7-1	01/96
19.1 ± 0.5	L	4.00	ANU/Samsung AIT AUS/KR	PESC, single phosph. diff. Note 2	35.5	0.662	81.3	ANU1/EC5-1	01/96
18.6 ± 0.4	L	4.10	ISFH, Emmerthal, D	MINP cell, mask free shallow angle evaporation	36.2	0.654	78.4	ISF9/MV37-9	04/96
18.5 ± 0.5	L	3.90	ISFH, Emmerthal, D	FZ-Si MIS-IL	39.3	0.615	76.7	ISF016/AM54/6	09/97
18.4 ± 0.4	L	25.00	SSG, München, D	FZ-material	37.8	0.653	74.7	SSG50/K37	05/95
18.3 ± 0.4	L	21.20	ISE, Freiburg, D	FZ, 2ARC, no texturing	35.2	0.661	78.7	ISE127/DJK19-1	01/96
18.3 ± 0.5	L	25.00	SSG, München, D	CZ-material	37.6	0.641	75.8	SSG49/K22	05/95
17.5 ± 0.4	P	100.50	ASE, Heilbronn, D	CZ material (FEW), n+pp+	37.2	0.612	76.6	DAH2 / 1A	09/93
17.1 ± 0.3	L	4.10	PSI, Villigen, CH	n- type emitter, cell thickness 215 µm (note 2)	31.4	0.672	81.3	PSI3 / W8-119CT	04/94
17.1 ± 0.4	L	89.80	IMEC, Leuven, B	Cz-Si, selective emitter, sreen-printed contacts	36.9	0.621	74.7	IMC019/Z735	06/98
17.1 ± 0.4	L	4.00	ISFH, Emmerthal, D	Truncated pyramid MIS-IL	35.5	0.639	75.5	ISF5/951001PrI	10/95
16.8 ± 0.4	L	105.00	SSG, München, D	CZ, screen printed BSF cell	35.0	0.621	77.0	SSG059#2	03/96
16.7 ± 0.3	P	142.90	BP Solar, E	high efficiency plant Madrid	34.6	0.614	78.6	BPS11 / TC 11	04/94
16.7 ± 0.3	L	95.10	IMEC, Leuven, B	Cz-Si, select. screen printed diffus. and metallisation	32.3	0.618	76.3	IMC014/2623F7	12/97
16.6 ± 0.3	L	4.00	LME/USP-INPE, Sao Paulo, BRA	FZ-Si	33.2	0.639	78.2	UPM004/N-7-2/LME	03/98
16.3 ± 0.3	L	4.10	PSI, Villigen, CH	n- type emitter, cell thickness 200 µm (note 2)	29.6	0.677	81.3	PSI3 / W8-20MC	04/94
15.8 ± 0.3	P	97.90	SSG, München, D	CZ material, 12 kW production, HEPCO	33.8	0.614	76.2	SSG22 / HEPC 1-2	12/93
15.7 ± 0.3	L	4.00	ISFH, Emmerthal, D	FZ-mat., MIS-IL, 300 µ 0.6 Ohm cm	35.6	0.595	74.4	ISF3/MIS-IL	08/95
15.6 ± 0.3	P	96.50	NAPS, Espoo, SF	CZ tri-grain material (note1)	33.9	0.613	75.0	NAP1/TC93	11/94
15.3 ± 0.3	L	100.40	ASE, Alzenau, D	CZ material	33.1	0.605	76.3	ASA4/AM801	11/94
15.3 ± 0.3	L	98.50	BP Solar, U.K.	BSF and ARC	32.9	0.605	76.7	BPS12/HE9	11/94
15.1 ± 0.3	L	4.00	ASE, Alzenau, D	MIS	32.3	0.617	75.5	NUK2 / KZ169	01/80
14.7 ± 0.3	L	1.00	MPI, Stuttgart, D	LPE base 16.8 µm	27.2	0.659	82.2	MPI7 / 953	10/92
14.5 ± 0.3	L	4.00	Univ. Konstanz, D	SIPOS	32.6	0.623	71.6	010UNK/507174	12/96
14.4 ± 0.3	L	4.00	USP/LME-INPE,S.Paulo, BRA	FZ- Si, BSF, 1.0 Ohm cm	30.1	0.622	76.9	UPM1/ LME- S64	02/95
14.3 ± 0.3	P	100.90	ASE, Heilbronn, D	CZ-mat. Bayer Solar GmbH, n+p, no interconn. (note 1)	31.3	0.602	75.8	DAH12/F101-127	11/94
14.1 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "steel blue"	29.7	0.603	78.5	BPS17/B-5	05/95
14.0 ± 0.3	L	68.40	VIESH, Moscow, R		31.1	0.611	73.5	VIS3 / -	04/92
13.5 ± 0.3	P	103.00	BP Solar, U.K.	BSF, no ARC	30.1	0.599	75.2	BPS13/LE2	11/94
12.4 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "gold"	26.4	0.601	78.2	BPS15/G-13	05/95
12.2 ± 0.3	L	143.00	BP Solar, U.K.	coloured LGBG- cell, "magenta"	26.2	0.597	77.9	BPS16/M-21	05/95
12.1 ± 0.3	P	67.40	Saturn, Krasnodar, R	for module type BS55	26.7	0.610	74.3	SAT10/#2	07/95
11.5 ± 0.3	L	1.00	MPI, Stuttgart, D	LPE base 4.2 µm	21.4	0.662	81.1	MPI8MW-54	12/92
11.2 ± 0.3	P	64.90	Saturn, Krasnodar, R	for module type BS50	24.8	0.597	76.0	SAT12	07/95

silicon cells multicrystalline

$\eta \pm U_{95}$ [%]	Lab. Prod.	A [cm²]	Manufacturer	Remarks	j_{sc} [mA/cm²]	V_{oc} [V]	FF [%]	Identification	Date
17.4 ± 0.4	L	21.20	ISE, Freiburg, D	Eurosolarx, 2ARC, oxide passiv.	34.4	0.637	79.2	176ISE/C15-7	03/97
16.9 ± 0.4	L	21.20	ISE, Freiburg, D	Baysix material (Bayer ex Freiberg)	34.8	0.617	78.8	ISE202/CB29-7	03/98
16.8 ± 0.3	L	21.20	ISE, Freiburg, D	Baysix, 2ARC, no texturing	34.3	0.621	78.8	ISE130/DJK19-11	01/96
16.5 ± 0.3	L	4.00	IMEC, Leuven, B	POLIX material	33.5	0.638	77.4	IMC9PB1-4	01/94
16.5 ± 0.4	L	98.00	IMEC, Leuven, B	screen printed contacts, mechanically textured surface	35.5	0.612	75.7	IMC018/2	06/98
16.5 ± 0.3	L	3.90	ISFH, Emmerthal, D	Baysix, MISn+p cell, SiN passiv., no text.	33.5	0.634	77.6	ISF017/HNAM2	12/97
16.4 ± 0.3	L	98.00	ASE, Heilbronn, D	Baysix material, no interconnectors (note 1)	33.4	0.622	79.0	TFK45 / 214-34-2	11/92
16.3 ± 0.3	L	98.10	IMEC, Leuven, B	Baysix mat., screen printed contacts	34.5	0.624	75.9	IMC016/19	02/98
16.2 ± 0.3	L	4.00	ISE, Freiburg, D	Baysix material, no interconnectors (note 1)	33.3	0.632	76.8	ISE57 / MCB 3.2	01/93
16.0 ± 0.3	L	3.90	IMEC, Leuven, B	Eurosolare substrate	34.2	0.604	77.8	IMC5 / F5D2	01/93
15.9 ± 0.3	L	95.80	IMEC, Leuven, B	BAYSIX screen printed contacts	33.3	0.620	77.2	IMC13/2446-B3	07/96
14.4 ± 0.3	L	25.00	SSG, München, D	Baysix material	30.9	0.612	76.2	SSG29 / G65	03/94
13.7 ± 0.3	L	100.20	ASE Alzenau, D; PIKLINGTON SOLAR INT.	cell recycled from module	31.5	0.599	72.4	ASA032/B10/12	05/98
13.7 ± 0.3	L	99.90	ASE, Heilbronn, D	Baysix material, n+p, screenprinted contacts	29.3	0.605	77.0	ASH3/PMC1-1	11/94
13.6 ± 0.3	L	92.20	IMEC, Leuven, B	Eurosolare substrate, no interconnectors (note 1)	31.1	0.595	73.5	IMC4/ -	01/93
13.2 ± 0.3	L	4.00	Univ. Konstanz, D	SIPOS/Bayer SOPLIN	27.8	0.611	77.7	011UNK/507D12	12/96
13.1 ± 0.3	P	100.20	ASE, Heilbronn, D	Baysix material, no interconnectors (note 1)	28.5	0.599	76.7	DAH13/B1C2-147	11/94
11.2 ± 0.3	L	4.10	MPI, Stuttgart, D	thin film LPE, base 26µm	24.2	0.643	72.1	MPI9 / 2G5	03/94
11.1 ± 0.3	L	4.00	Uni Konstanz	Bayer RGS material	28.4	0.538	72.4	014UNK/100.4d	07/97

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Session 9 Fundamentals I
Room C 13 (Wed) 09:00 – 10:40

Chairperson: J. R. Sites Colorado State Univ. USA.
K. J. Kim Korea University Korea

Session 10 III-V and Space Cells I
Pearl Room 13 (Wed) 09:00 – 10:40

Chairperson: A. Freundlich Univ. of Houston USA
S. Bailey NASA USA

Session 11 Crystalline Si Solar Cells II
Room A 13(Wed) 11:00 – 12:20

Chairperson: A. Rohatgi Georgia Inst. Of Tech. USA
Y. K. Kim Univ. of Inchon Korea

A High-Efficiency HIT™ Solar Cell (21.0% ~100cm^2) with Excellent Interface Properties

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ABSTRACT

The amorphous silicon (a-Si)/monocrystalline silicon (c-Si) Heterojunction with Intrinsic Thin-layer (HIT™) solar cell developed by Sanyo Electric offers many excellent features, including high conversion efficiency, a low-cost potential with thin wafer thickness, and double surface power generation. We have achieved the new world highest conversion efficiency of 21.0% with a high open circuit voltage of 714 mV on a solar cell with the HIT structure for a large area of 100 cm^2. The essence of this high performance comes from the excellent interface passivation of the a-Si/c-Si hetero-interface.

1. Introduction

Since the first silicon solar cell was reported in 1954, the conversion efficiency of c-Si solar cells has been dramatically improved. This is due mainly to progress in cell design, Si material properties, and processing technologies. The highest efficiency for small-area Si solar cells is 24.7% for the Passivated Emitter Rear Locally-diffused (PERL) structure solar cell by UNSW [1]. For a large-area Si solar cell of 100 cm^2, a conversion efficiency of 20.2% has been achieved by FhG-ISE [2]. These solar cells, however, require some photo masking processes and high-temperature cycling of furnace steps, which increase of manufacturing costs.

We have developed the HIT cell using suitable processes for mass production. This paper reports on the structure, features and interface passivation properties of the HIT cell.

2. Structure and efficiency of the HIT cell

Figure 1 shows a schematic diagram of the HIT cell. The HIT cell is composed of a textured n-type c-Si wafer (solar grade CZ-Si) sandwiched between p/i a-Si:H films on the illuminated side and i/n a-Si:H films as a BSF(Back Surface Field) structure on the back side. These films are deposited by plasma CVD. Transparent conductive oxide (TCO) films and Ag collector electrodes are formed on both doped a-Si:H layers to give the HIT solar cell a vertically symmetrical structure. Furthermore, the HIT cell is formed at low temperatures, i.e., below 200℃ in every production process. These structural and processing features ease thermal stress and damage, and allow the use of thin Si wafers. Therefore we can use Si wafer less than 200 µm thick in mass production, which is thinner than that of conventional p-n diffused solar cells.

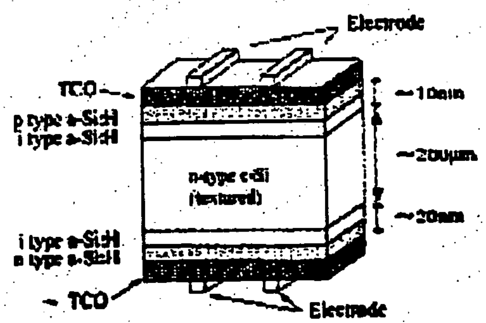

Fig. 1 Schematic diagram of the HIT cell structure.

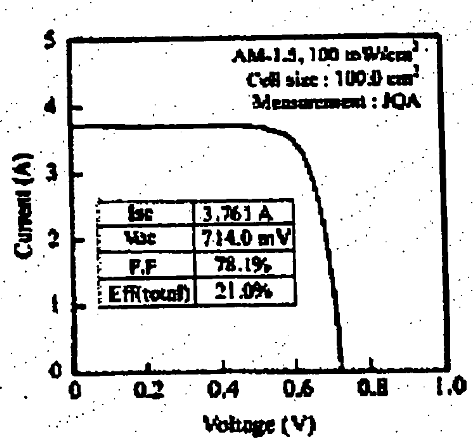

Fig. 2 Illuminated I-V characteristics of the HIT cell confirmed by JQA.

Figure 2 shows the improved I-V characteristics of the HIT cell as confirmed by JQA (Japan Quality Assurance organization). We improved our world's highest efficiency to 21.0% by optimizing the cell designs, using a 1 Ω cm low-cost solar grade CZ-Si wafer (100 cm^2). Here we achieved a high open

circuit voltage of 714 mV. While solar cells with a Voc exceeding 710 mV have been reported previously [3,4], they use a flat substrate to increase the Voc, ignoring the current value and solar cell output. The high Voc value exceeding 710 mV of the HIT cell confirms the importance of the junction formation technology, including interface passivation.

3. Passivation performance of the HIT cell

To directly observe the passivation effect of the intrinsic a-Si layers, we evaluated the minority carrier lifetimes of the HIT cells by the μ-PCD method [5]. We made a series of measurements on more than 30 different wafer lots. In this experiment, two adjacent wafers in one pack of a wafer lot were selected as a pair, to avoid any deviation in the bulk lifetime of the wafers as much as possible. After conducting the normal texturing and cleaning processes on the wafers, one of each wafer pair was passivated with iodine-methanol, and the other was sent to the a-Si deposition process for HIT structure fabrication. Iodine termination is a common technique for measuring the carrier lifetime of c-Si wafers.

Figure 3 shows the lifetime of wafers with the HIT structure. Each lifetime data is plotted to that of the iodine-terminated c-Si wafer. The HIT structure wafers achieved higher carrier lifetimes than the wafers subjected to iodine passivation, indicating that extremely good surface passivation had occurred. It has been reported that the passivation effect of iodine passivation exceeds that achieved by surface passivation with a SiO_2 film using thermal oxidation [6].

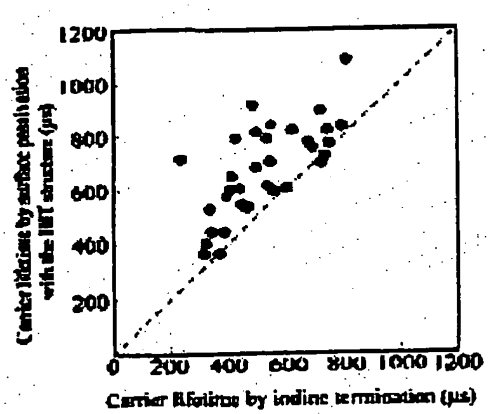

Fig. 3 Comparison of Si wafer carrier lifetimes for different passivation processes. The dotted line indicates matching for both processes.

From the above results, the HIT cell is clearly an excellent structure with respect to surface passivation. We believe that the passivation effect of the HIT cell includes the carrier separation effect at the c-Si/a-Si junction and the passivation effect of the c-Si surface.

4. Conclusion

For the further development of the HIT cell, it is important to advance the interface passivation properties.

We have achieved the world's highest total area conversion efficiency of 21.0% and a high open circuit voltage of 719 mV in the HIT cell (cell size: 100 cm^2). In the HIT cell, the excellent surface passivation with a-Si:H layers contributes a great deal to this high performance. The carrier lifetime measured by the μ-PCD method turned out to be the effective method.

We will continue investigating surface passivation using the a-Si:H layer of the HIT cell and will aim at still higher performance by improving the surface passivation properties.

Acknowledgement

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